SIRAS-G, The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit

Reference Number B5P3
2004 ESTO ESTC Conference
Palo Alto, CA

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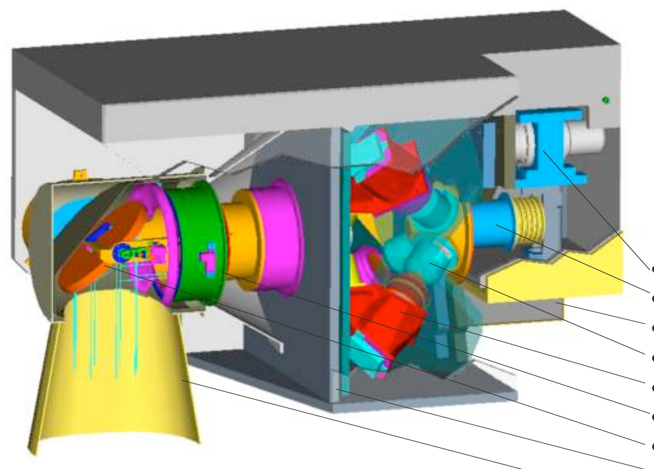
The SIRAS-G Program

- **SIRAS-G: Spaceborne Infrared Atmospheric Sounder for Geosynchronous Orbit**
  - SIRAS-G is an instrument concept for infrared sounding at a moderate spectral resolution ($\lambda/\Delta\lambda$) of 800 – 1100, operating from 3.35 – 15.4μm
  - ♣ Grating spectrometers provide fine spectral separation
  - ♣ The flight instrument divides this spectral range into 4 spectrometer channels
  - ♣ Lab Demo will be single channel

Table 1. SIRAS-G Grating Spectrometers

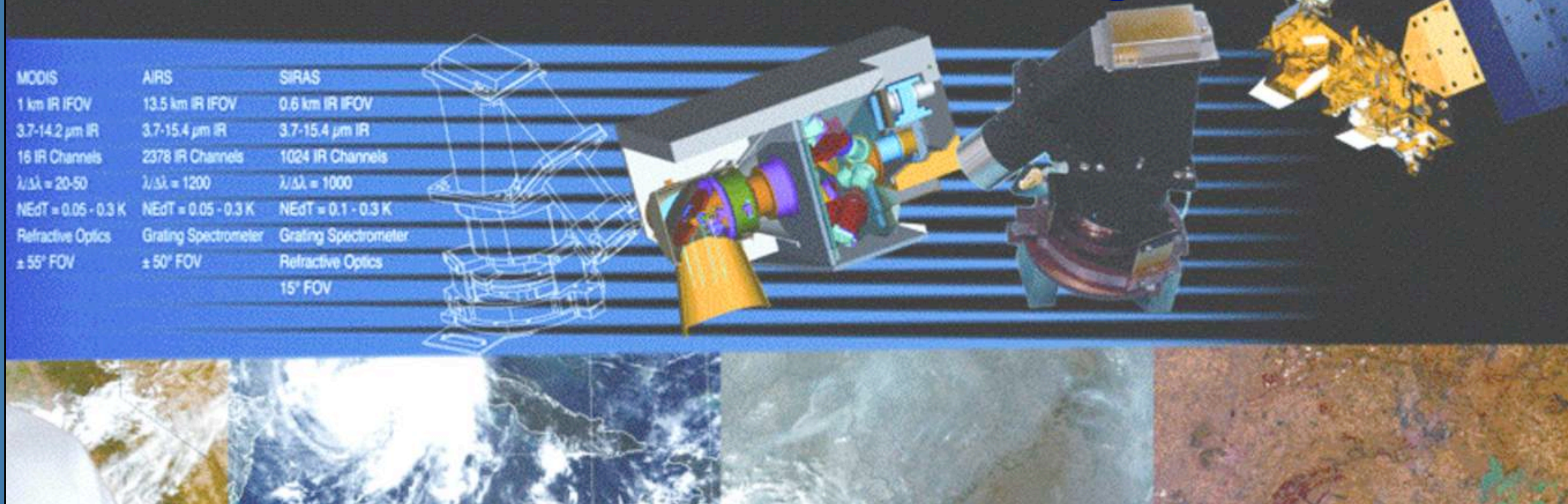
Spect	Band (μm)	Comments
1	3.35-4.8	Build in 2003 IIP
2	6.2-8.22	Design in 2003 IIP
3	8.8-12.0	Design in 2003 IIP
4	12.3-14.8	Built in 1999 IIP



	SIRAS-L	SIRAS-G
Size	0.13 m^3	0.19 m^3
Mass	50 kg	50 kg
Power	100W	100W
Rate	1.42 Mbps	2.5 Mbps

*** Common Spectrometer, FPA, Dewar, and Cooler Design for LEO or GEO**

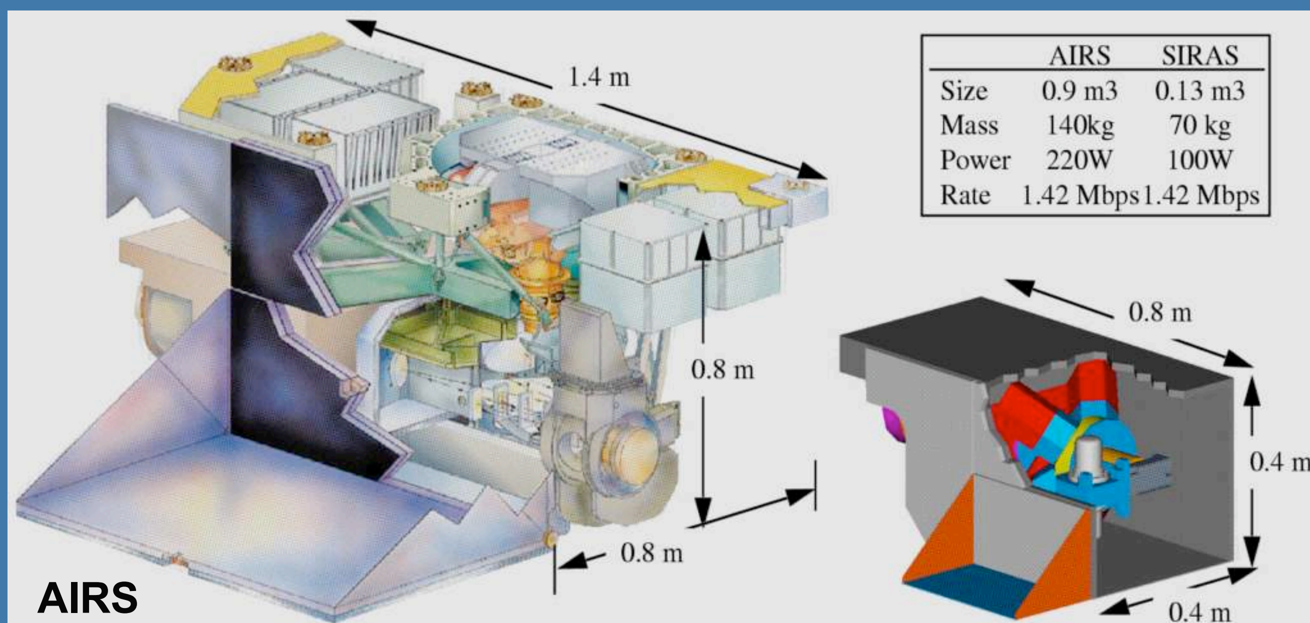
NASA’s Instrument Incubator Program



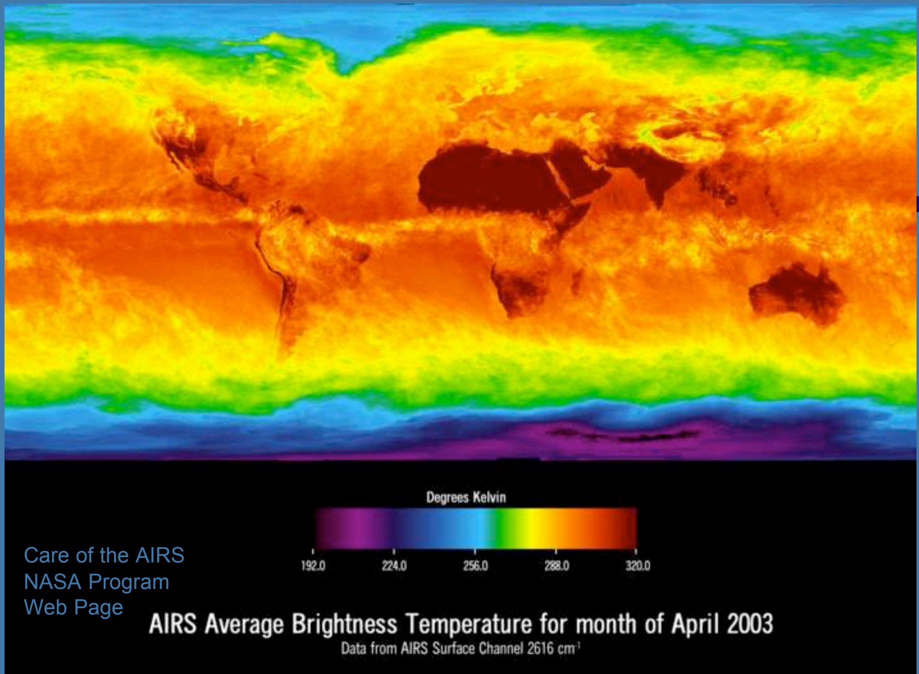
- SIRAS-G was selected for NASA’s Instrument Incubator Program in January 2003
- **IIP was developed to foster the** development of innovative remote-sensing concepts **and the assessment of these concepts in ground, aircraft, or engineering model demonstrations.**
- **New and innovative technologies targeted to future flight instruments that are** smaller, less resource intensive, less costly, and require less build time**.**
- **By investing early in the development life cycle of an instrument and** demonstrating performance in ground based or aircraft instrumentation**, flight builds will also encounter less development risk and therefore less cost and schedule uncertainty.**
- **The Program’s aim is to provide a continuing source of mature instrument designs merging state-of-the-art technologies with measurement objectives available for use in the next generation of Earth science missions.**

SIRAS-G History

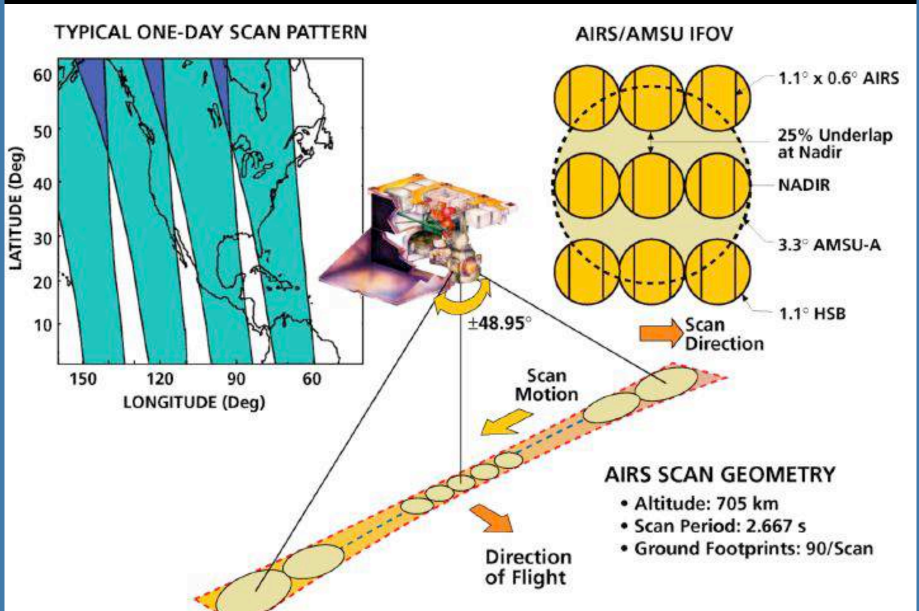
- SIRAS was originally conceived as a smaller, lower mass, less costly follow-on instrument for AIRS (Atmospheric Infrared Sounder)
- In 1999, JPL headed up the Spaceborne Infrared Atmospheric Sounder (SIRAS) IIP
  - PI: Harmut Aumann (JPL, Chief Scientist on AIRS)
  - Technical Lead: Tom Pagano (JPL, AIRS Program Manager)
  - Ball Technical Lead: Tom Kampe



	AIRS	SIRAS
Size	0.9 m3	0.13 m3
Mass	140kg	70 kg
Power	220W	100W
Rate	1.42 Mbps	1.42 Mbps



Care of the AIRS NASA Program Web Page



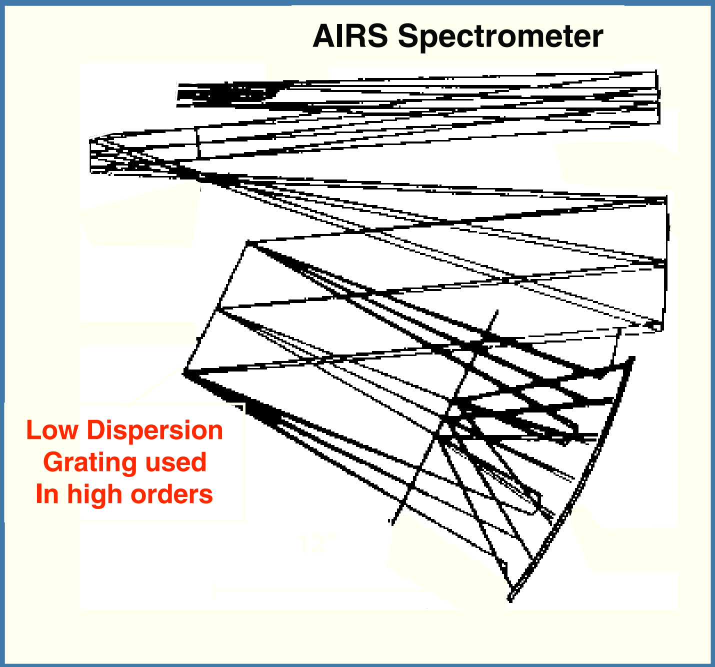
Care of the NASA AIRS Program Web Page

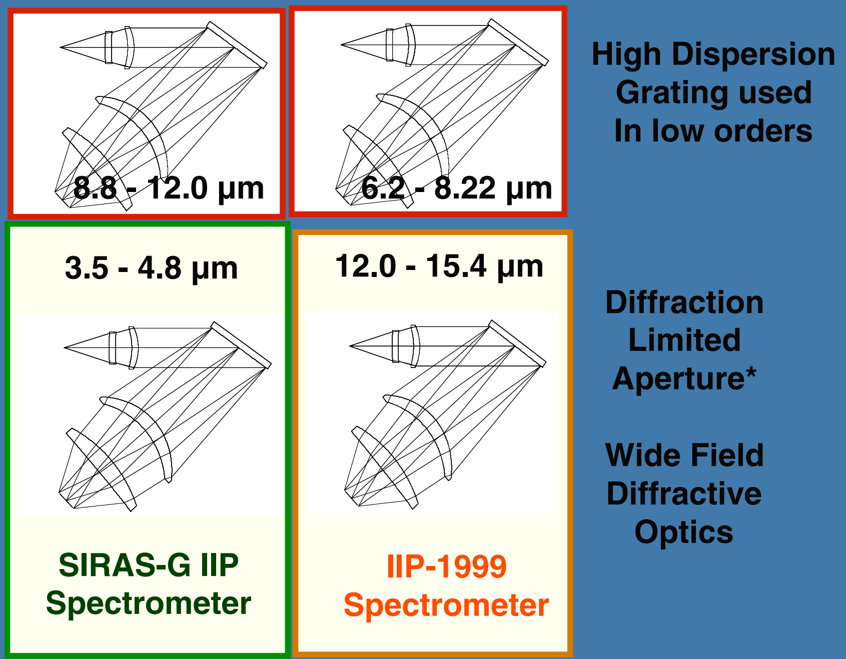
Background

- AIRS is an IR Sounder making highly accurate measurements of air temperature, humidity, clouds, and surface temperature
- The data collected by AIRS will be used by scientists around the world to better understand weather and climate
- AIRS is one of six instruments onboard NASA's Aqua spacecraft
- The PI on AIRS is Dr. Moustafa Chahine (JPL)

Follow-On To AIRS

- SIRAS replaces the single large eschelle grating in the complex pupil-imaging instrument architecture of AIRS with 4 spectrometer modules
- This leads to reduced total mass, volume and power
- On the SIRAS Program, we designed, built, and tested one of the 4 spectrometer modules

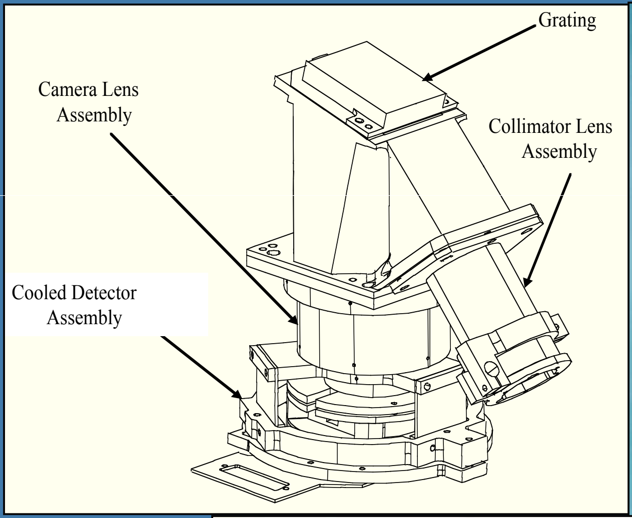


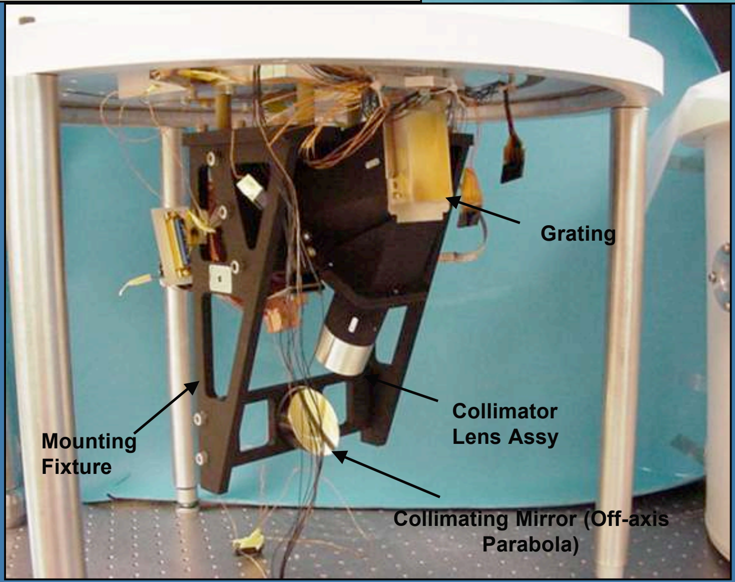


SIRAS Spectrometers

SIRAS-1999 IIP - What Was Achieved?

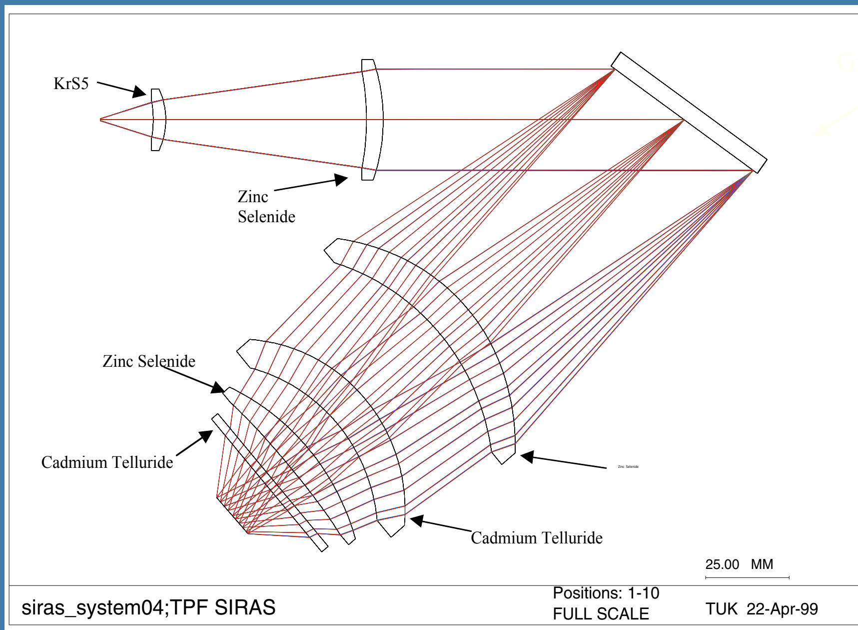
- **Designed, built & cryogenically tested the LLWIR (12-15.4μm) spectrometer**
  - Selected the LLWIR spectrometer since it represented the greatest challenge (material choices, detector cut-off, etc.)
- **Developed test facilities for testing the spectrometer at cryogenic temperatures**
- **Integrated an AIRS M1 detector array (on-loan from the AIRS program) and used a detector test set loaned from LMIRS**
- **Developed data collection and control software**
- This effort completed in 12-months





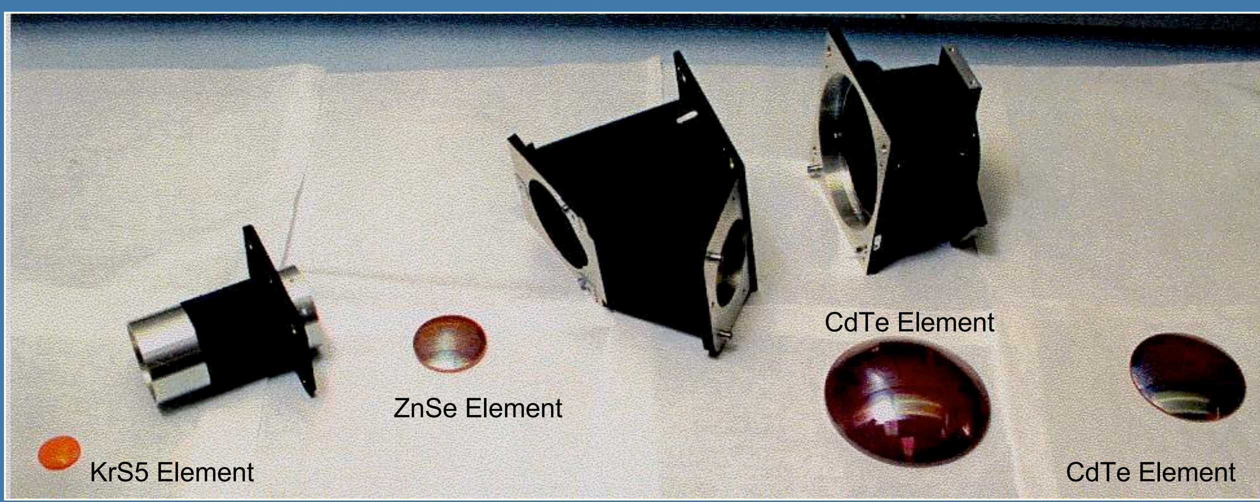
SIRAS SPECTROMETER IN TEST DEWAR

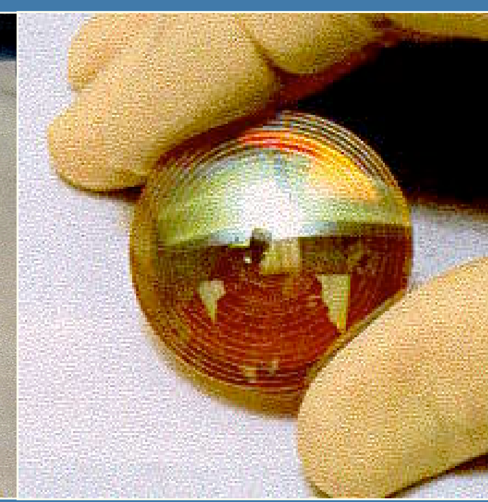
SIRAS-1999



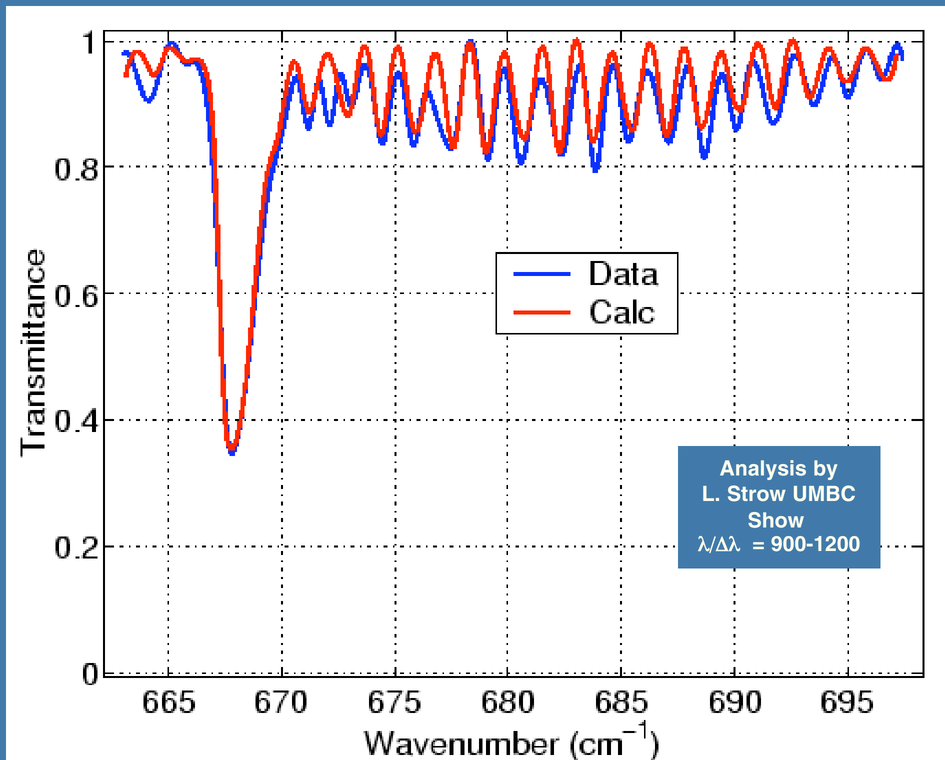
Optical Subassemblies

- **2-element Collimator**
  - E1: All-spherical KrS5
  - E2: Hybrid asp/diff ZnSe
- **Planar Grating**
- **3-element Camera**
  - E3: ZnSe element w/asp
  - E4: All-spherical CdTe
  - E5: Hybrid asp/diff ZnSe

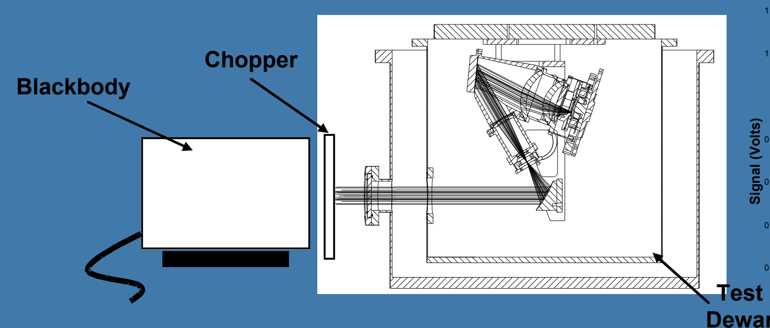


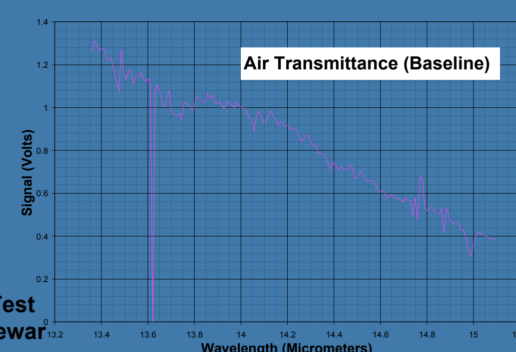


Excellent Spectral Performance on SIRAS-1999



- Measured data were analyzed for spectral resolution by comparing them to theoretical 3-m path atmospheric transmission spectra with varying spectral response widths
- Response widths were varied until the resulting convolved modeled spectra matched the measured spectra
- Measured CO_2 spectra show spectral resolution (>900) achieved



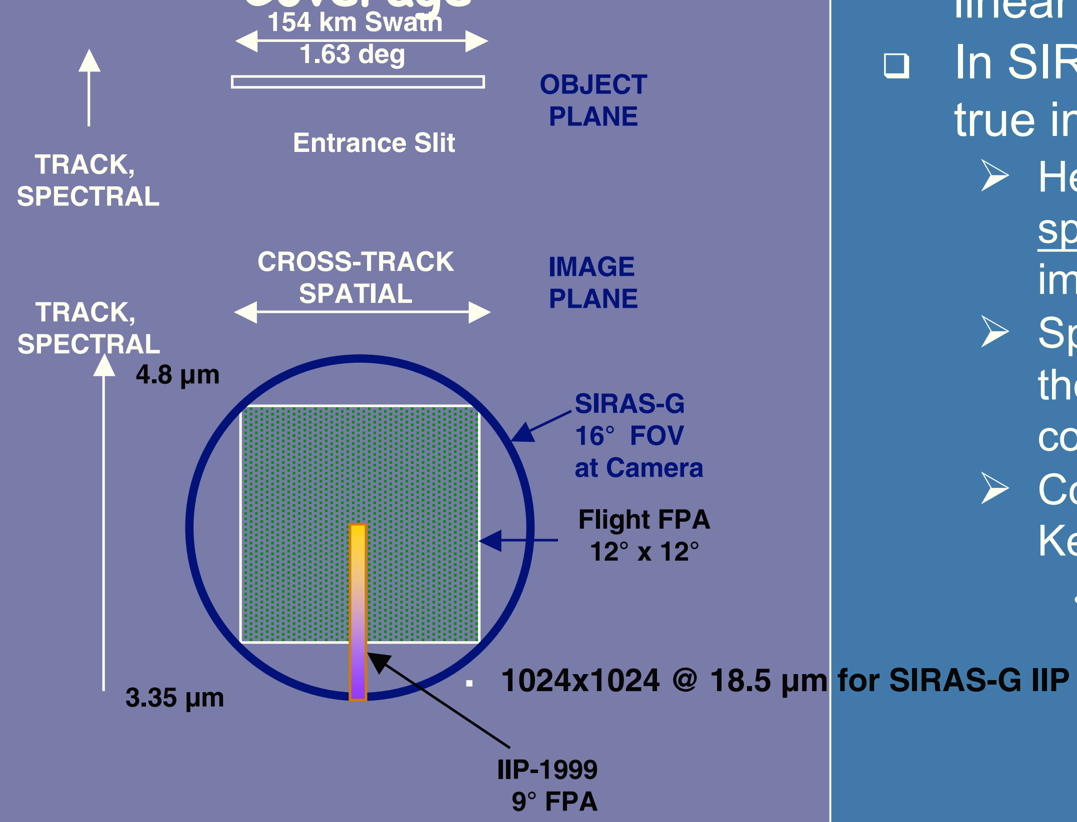


What is SIRAS-G?

- **SIRAS-G is an instrument concept for an Infrared Sounder in Geosynchronous Orbit**
- **SIRAS-G utilizes grating spectrometer technology based on AIRS and SIRAS-1999 heritage**
- **The purpose of the SIRAS-G IIP program is to further develop the SIRAS-G concept and build a laboratory hardware demonstration**
  - Increase Technology Readiness from TRL-3 to TRL-5 or 6
  - Demonstrate an workable end-to-end system incorporating new technologies including:
    - **Refractive grating spectrometers**
    - **Optically-Enhanced FPA Dewar**
    - **Active Cooling**

How Does SIRAS-G Differ From SIRAS?

SIRAS-G Provides Broad Spatial Coverage

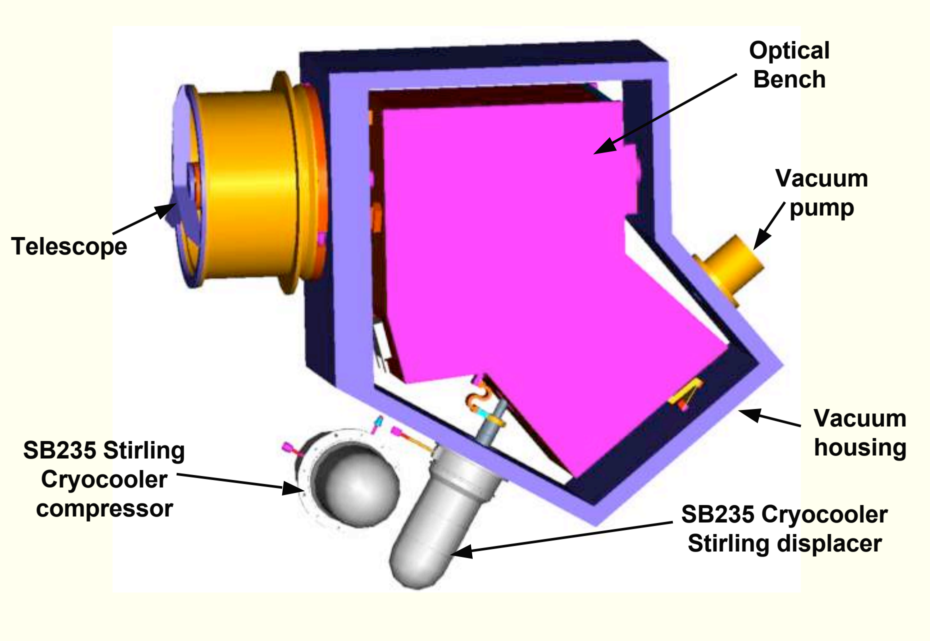


- The Spectrometer on SIRAS imaged a single ground IFOV. The spectrum was dispersed along a linear detector array.
- In SIRAS-G, we will be building a true imaging spectrometer
  - Here, we have an appreciable spatial FOV in the camera of 16^0 imaged along rows of detectors
  - Spectral information dispersed in the orthogonal direction, along columns of detectors
  - Control of Spectral Smile and Keystone Distortion are critical
    - In the baseline optical design, these are controlled to less than 25% of a pixel across the full FOV

Laboratory Demonstration Instrument

Goal is to design, build and test a laboratory demonstration instrument including:

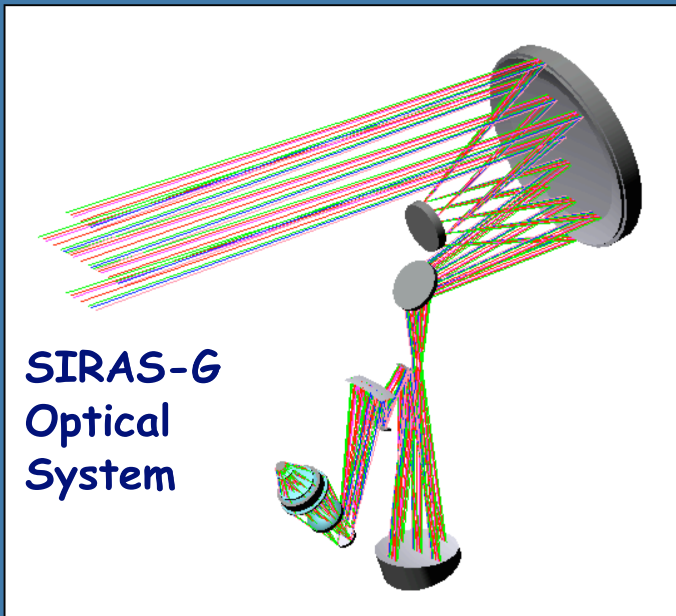
- Telescope
  - A 3-mirror anastigmat is baselined for the flight instrument, but…
  - We are also considering an on-axis obscured Ritchey-Chrieten telescope w/field flattener due to funding constraints.
- Reflective collimator
- Spectral selection module (beamsplitter assembly)
- A single spectrometer module (3.4 - 5μm baseline)
- A 1024 x 1024 (Eng Grade) FPA
- Optically-Enhanced Cryogenic Dewar
- Ball Aerospace & Technologies SB235 Cryocooler



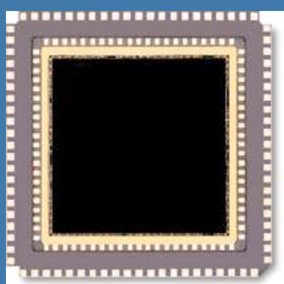
Ball SB235 Cryocooler Parameters

- 3rd Generation Multi-stage 35 K Cooler
- Performance: 0.5 W @ 40 K & 3.5 W @ 100 K for 90 W motor
- 99% reliability at 10 years
- 10.5 kg mass
- Verified non-contacting operation over wide temperature range (-60 to +80 ^{0}C)
- Active vibration isolation to below 0.10 N
- Fixed-regeneration cold finger capable of withstanding high side loads
- Inherently insensitive to 1-g orientation
- Proven and verified EM control features

Distortion Well Controlled



Keystone distortion and spectral smile less than 15% of a pixel over entire extent of 1024x1024 FPA



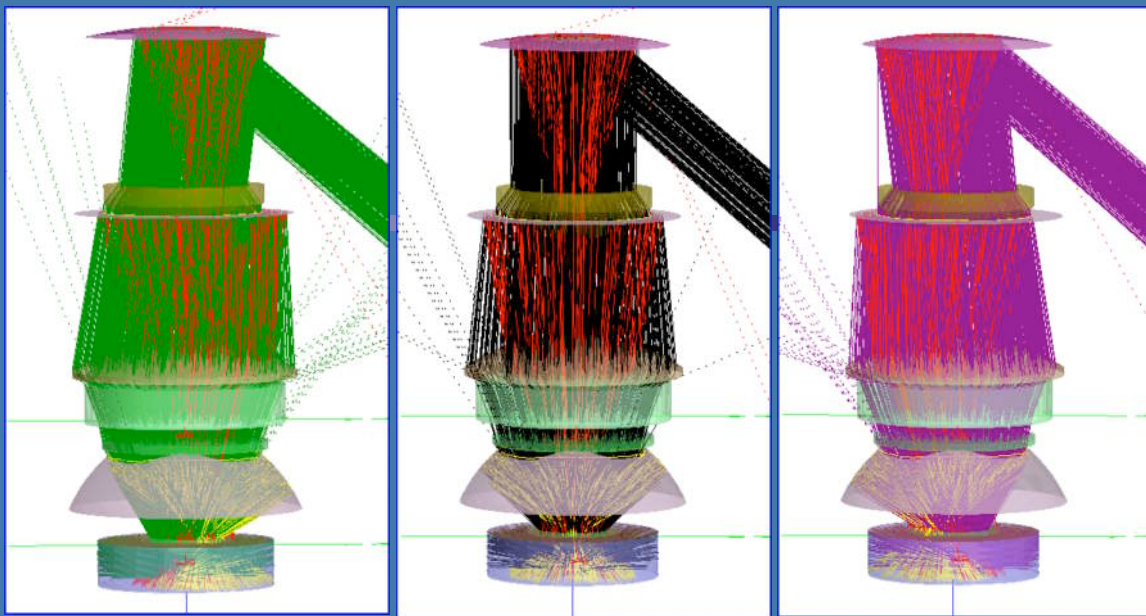
Rockwell Hawaii
5.0-micron Cut-Off
Infrared FPA

1024 x 1024
HgCdTe/CdZnTe

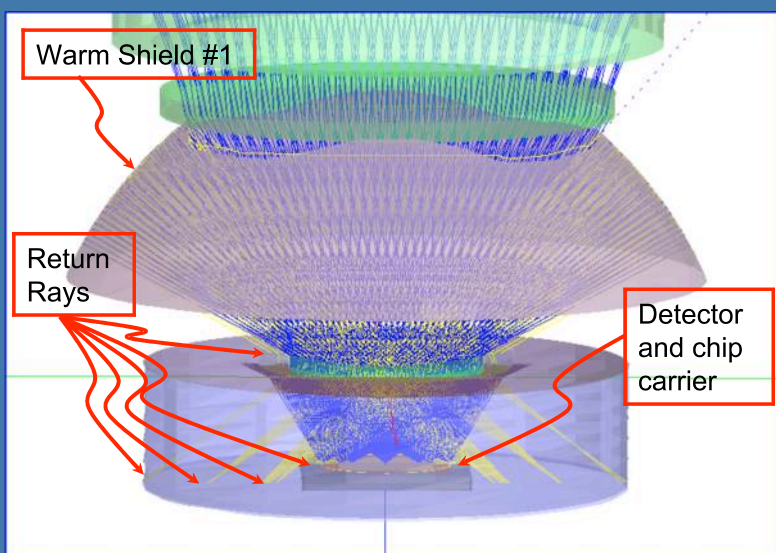
					Error to Center of FPA			
Field	**Paraxial (4.500 microns)**		**Measured (4.500 microns)**		**Error (mm)**		**Error (# pixels)**	
	Spatial (deg)	Spectral (deg)	Spatial (deg)	Spectral (deg)	Spatial	Spectral	Spatial	Spectral
f1	0.00000	9.47200	-1.15E-04	9.47574	-0.0001	0.0000	0.00	0.00
f2	4.73600	9.47200	4.73692	9.47435	0.0009	-0.0014	0.02	-0.04
f3	6.69670	9.47200	6.69774	9.47321	0.0011	-0.0025	0.03	-0.07
f4	9.47200	9.47200	9.47261	9.47096	0.0020	-0.0048	0.05	-0.13
f7	-9.47200	9.47200	-9.47483	9.47073	-0.0042	-0.0050	-0.11	-0.14
	Paraxial (3.925 microns)		**Measured (3.925 microns)**		**Error**		**Error (# pixels)**	
f1	0.00000	0.00000	5.51E-09	-4.56E-04	0.0000	0.0000	0.00	0.00
f2	4.73600	0.00000	4.73604	-3.29E-04	0.0000	0.0001	0.00	0.00
f3	6.69670	0.00000	6.69665	-3.59E-04	-0.0001	0.0001	0.00	0.00
f4	9.47200	0.00000	9.47061	-5.91E-04	-0.0014	-0.0001	-0.04	0.00
f7	-9.47200	0.00000	-9.47061	-8.20E-04	0.0014	-0.0004	0.04	-0.01
	Paraxial (3.350 microns)		**Measured (3.350 microns)**		**Error**		**Error (# pixels)**	
f1	0.00000	-9.47200	1.15E-04	-9.47274	0.0001	0.0000	0.00	0.00
f2	4.73600	-9.47200	4.73638	-9.47164	0.0003	0.0011	0.01	0.03
f3	6.69670	-9.47200	6.69696	-9.47073	0.0003	0.0020	0.01	0.05
f4	9.47200	-9.47200	9.4718	-9.46932	0.0012	0.0034	0.03	0.09
f7	-9.47200	-9.47200	-9.47157	-9.46955	-0.0010	0.0032	-0.03	0.09

Optically-Enhanced Dewar

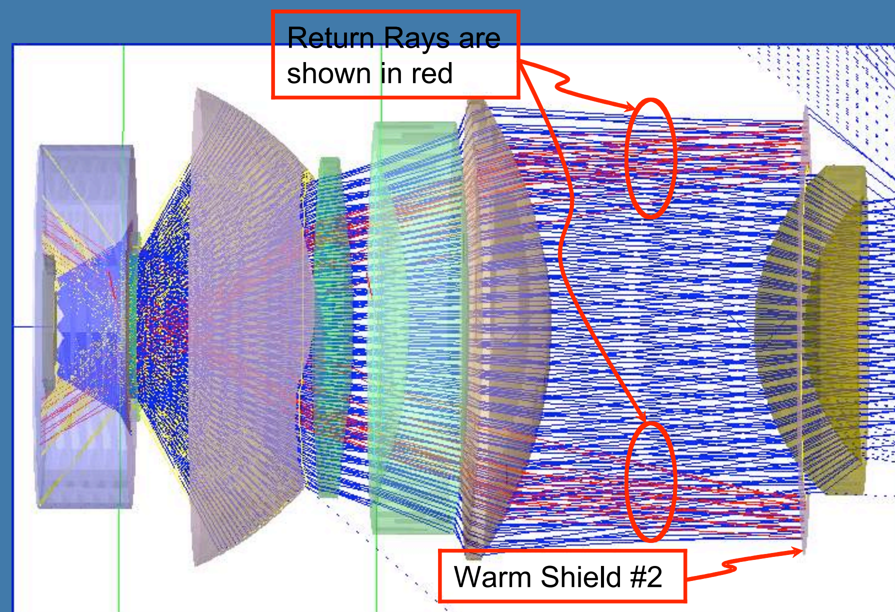
- With pupil at grating, cooling of entire camera to ~70K required for 100% Cold Stop Efficiency
- Use of *well-designed* reflective warm shields offers CTE of 90 to 95%
- Concept to be demonstrated on SIRAS-G



Ray traces from the three locations on the image plane corresponding to the wavelengths 3.35mm, 3.925mm, and 4.50mm



Warm Shield 1st Stage: Rays leaving the detector are blue & rays reflected off the warm shield are yellow.

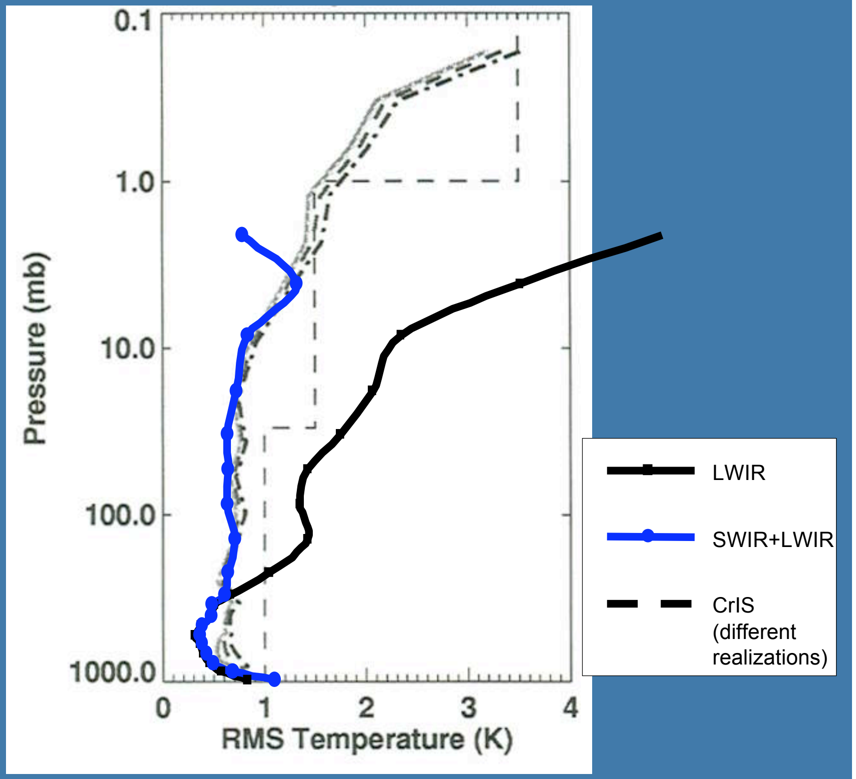


Second tier of warm shield captures a significant number of rays from the detector are outside lens aperture

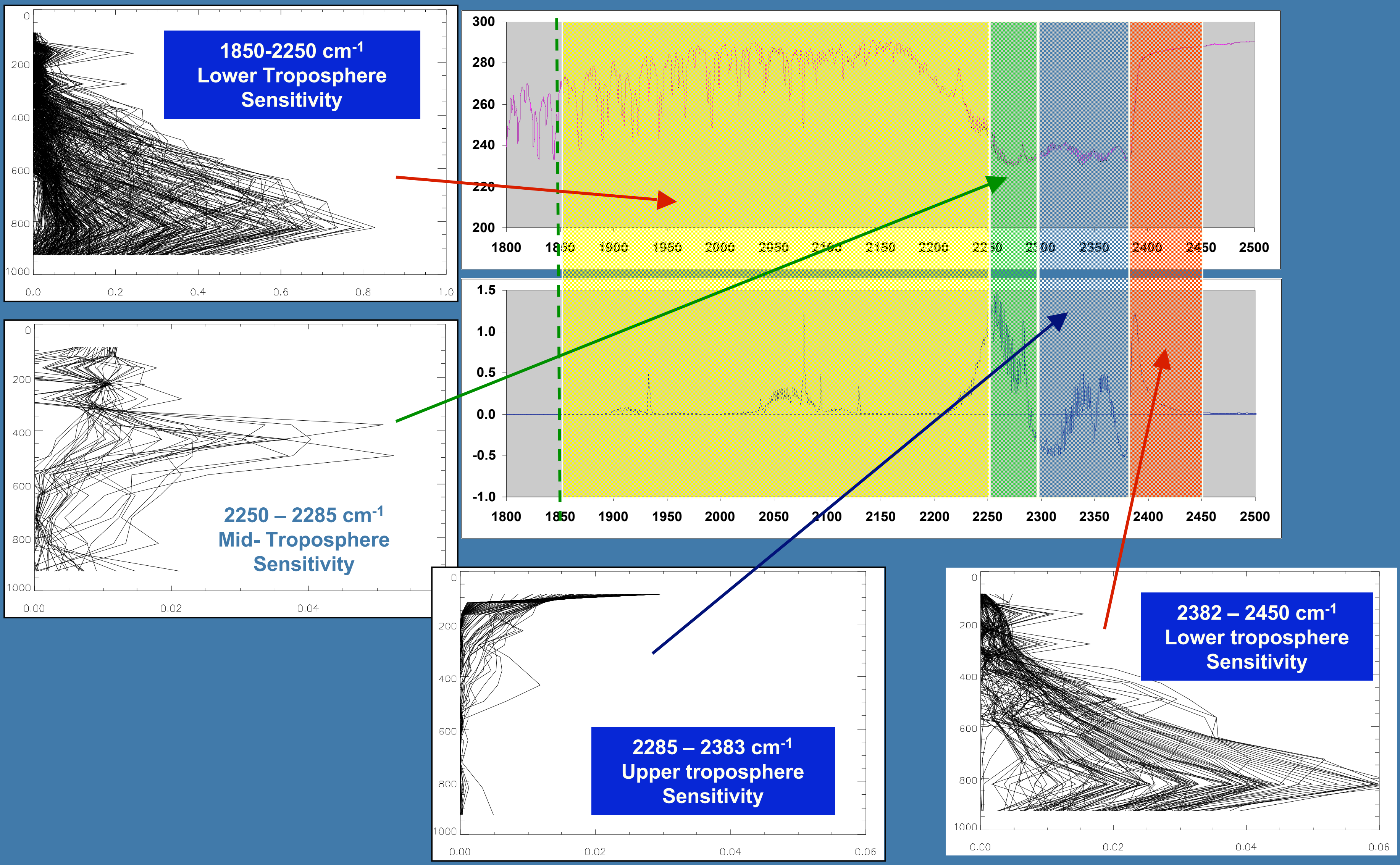
Forward Modeling Tools Developed for SIRAS-G

- ***Developing Radiative Transfer tools to support systems-level studies***
  - *Radiative transfer forward model using LBLRTM now largely in place*
    - *Supports trade studies to assess spectral resolution and spectral range versus noise for primary retrievals*
    - *Principal Component Analysis incorporated to reduce dimension and noise*
    - *Retrieval model employs optimal estimation method*
      - *Unconstrained Levenberg-Marquardt optimization (constrained Newton-Gauss produced similar RMS errors, but much slower)*
      - *Realistic but conservative Climatology/Forecast model*
  - *Extension to secondary products (in combination with IMOFPS)*
  - *Required software/algorithms in place*

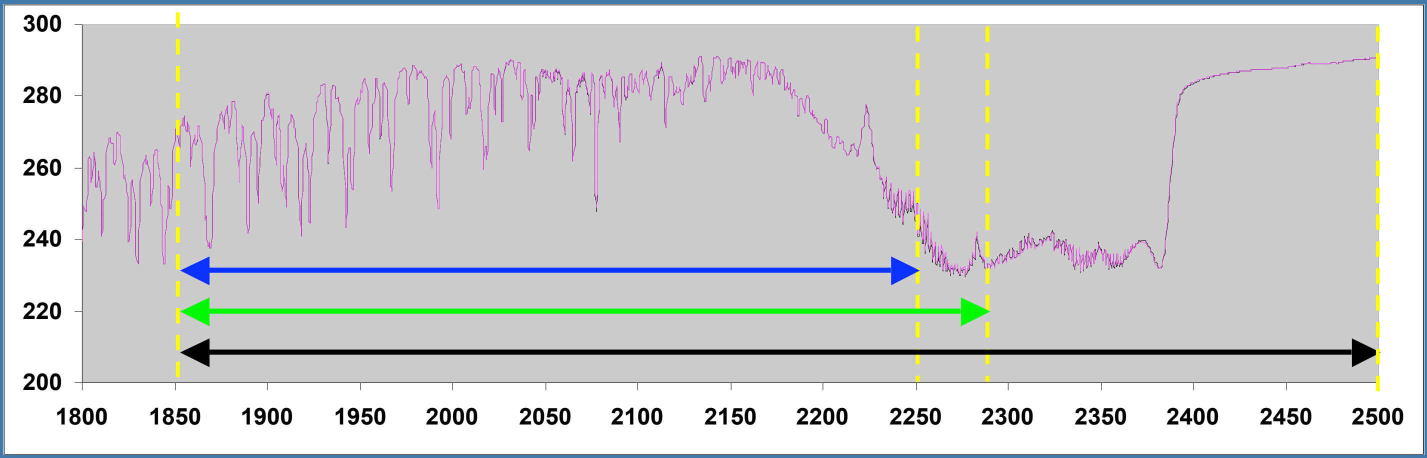
Comparison of CrIS and SIRAS-G Temperature Errors



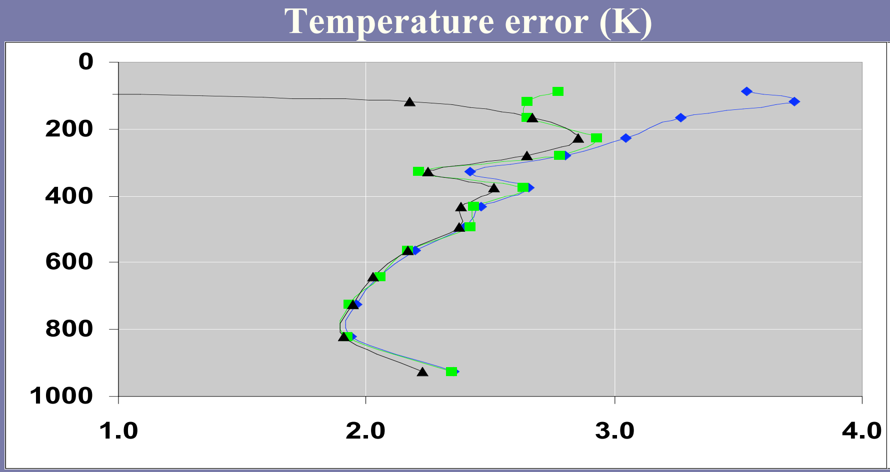
Spectrometer Spectral Range & Resolution Optimized Based on Temperature Weighting Functions

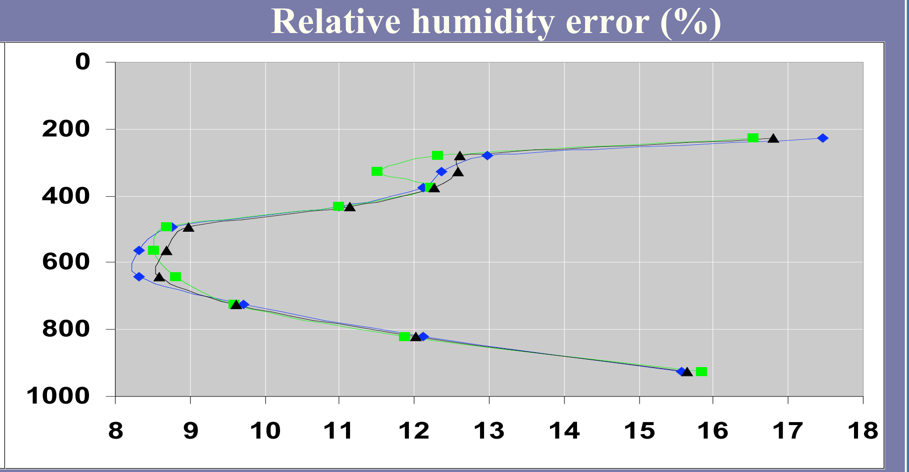


Performance Using MWIR Region Only



- Influence on spectral range on temperature and water vapor retrieval evaluated
- Good performance attainable with Lab Demo





System Configuration Studies

- **The feasibility of applying SIRAS to a variety of high-priority Earth science missions is being explored, including:**
- *Next-Generation Environmental Sounder from GEO*
  - Requirements for next generation GEO IR sounder were SIRAS-G baseline
  - Unlike competing technologies, SIRAS has no moving parts, requires no transforms to obtain spectra, and uses proven AIRS spectrometer technology and data processing algorithms.
- *Geostationary Atmospheric Chemistry Mission*
  - SIRAS-G part of instrument suite to measure trace gases (CO, CH_4, NO_x, & O_3)
  - Combining SIRAS-G and a multi-channel high-resolution spectrometer (IMOFPS) provides these measurements in a compact, solid-state instrument suite.
  - IMOFPS consists of three co-boresighted correlation spectrometers for determining vertical profiles of CO and column amounts of CO_2 and CH_4. The addition of a fourth spectrometer channel for measuring NO_x would provide a tracer of motion and cloud detection.
  - A two-channel version of SIRAS-G, one channel extending from 12.3-μm to 15-μm and a second centered at the 9.6-μm ozone band, with spectral resolution “tuned” appropriately in both channels, would provide temperature and water vapor sounding and ozone column.

AIRS Follow-On

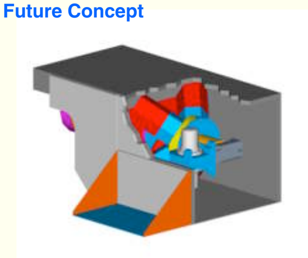
The Spaceborne Infrared Atmospheric Sounder for LEO (SIRAS-L)

EOS Terra, Aqua

MODIS

- 1 km IR IFOV
- 3.7-14.2 μm IR
- 16 IR Channels
- $\lambda/\Delta\lambda$ = 20-50
- NEdT = 0.05 - 0.3 K
- Refractive Optics
- ± 55° FOV

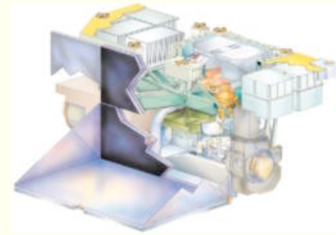
Future Concept



SIRAS-L

- 0.6 km IR IFOV
- 3.7-15.4 μm IR
- 1024 IR Channels
- $\lambda/\Delta\lambda$ = 1000
- Refractive Optics
- Grating Spectrometer
- NEdT = 0.1 - 0.3 K
- 15° FOV

EOS, Aqua



AIRS

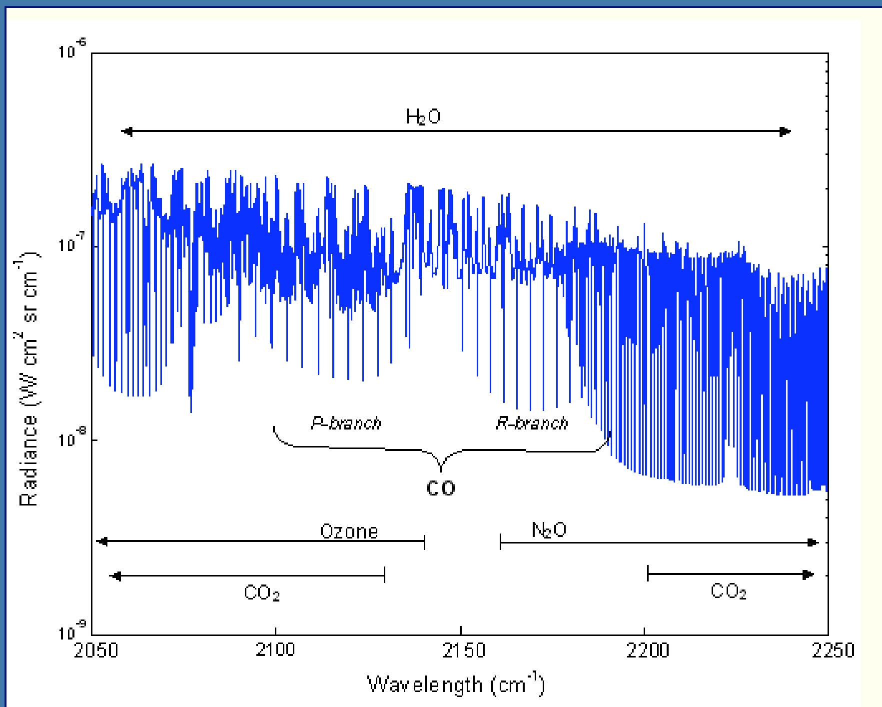
- 13.5 km IR IFOV
- 3.7-15.4 μm IR
- 2378 IR Channels
- $\lambda/\Delta\lambda$ = 1200
- Grating Spectrometer
- NEdT = 0.05 - 0.3 K
- ± 50° FOV

- SIRAS-L offers the high spatial resolution of MODIS and the high spectral resolution of AIRS.
- The presence of clouds significantly degrade the ability to achieve accurate temperature and water vapor retrievals.
- Future atmospheric sounding systems will require greatly enhanced spatial resolution. SIRAS-L offers a ground footprint of less than 0.6 km (as compared to AIRS at 13.5 km) without sacrificing SNR. The system is used in “pushbroom” mode to maximize integration time.

Other Opportunities – ESTO Measurement Priorities

- **IR Sounder for measuring cloud system structure, winds, ozone, trace gas precursors, temperature & water vapor profiles from GEO**
  - 4x4 km spatial resolution
  - 0.3 cm^{-1} spectral resolution
  - Cryo-cooling to 70K
- **IR Sounder to measure SST from LEO – measure atmospheric temperature & water vapor profiles, land surface temperature, cloud properties, radiative energy flux**
  - ~2400 high-spectral resolution bands from 3.7-15.4μm
  - ♣ WFOV IR optics
- **IR Sounder for measuring storm cell properties from UAV**
  - Measure temperature and water vapor profiles in and around storm cells
  - 0.5 cm^{-1} spectral resolution over 3.6-15.4 μm
  - ♣ SIRAS ideally suited to application since it has no moving parts and it is extremely robust

Complementary Developments at Ball IMOFPS High Resolution IR Spectrometer



Simulated Mid-Latitude Spectrum near the Fundamental Line Centers for CO

- IMOFPS is a high spectral resolution (0.1 cm^{-1}) spectrometer tuned to sample the absorption spectra of key trace gases
- IMOFPS increases the useable FOV over that of a conventional Fabry-Perot
- In addition, the unique correlation filter design provides excellent matching of the instrument transmission function to the non-periodic gas absorption features

Patent Applications have been filed by Ball Aerospace for the IMOFPS Correlation Filter and Anamorphic Optical System

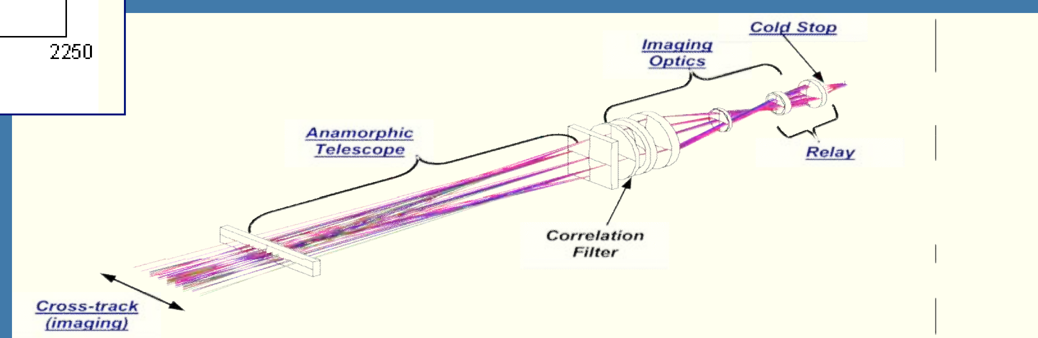
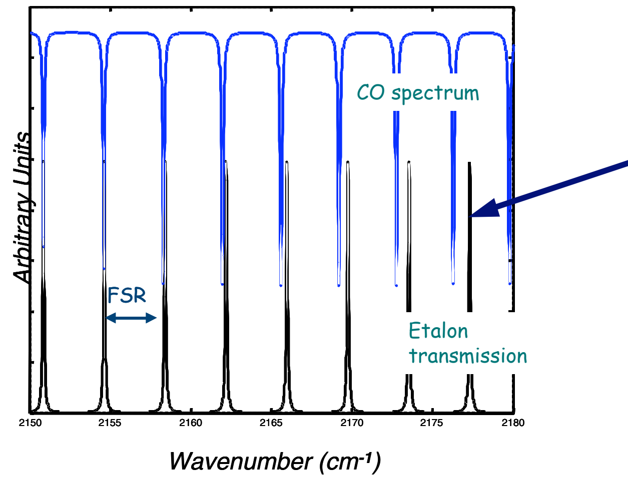


Figure 5. Optical system for a single spectrometer channel.

IMOFPS Improves on Conventional Fabry-Perot Implementation

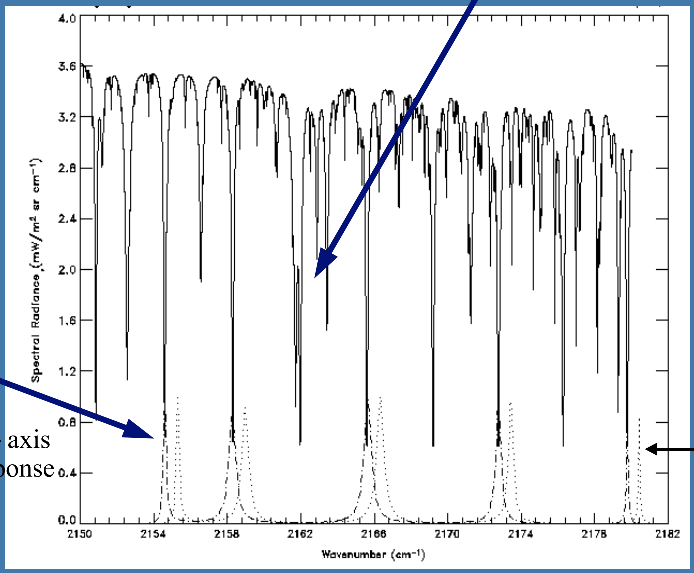


Etalon Free Spectral Range Mis-Match with Spectral Lines (CO Example)

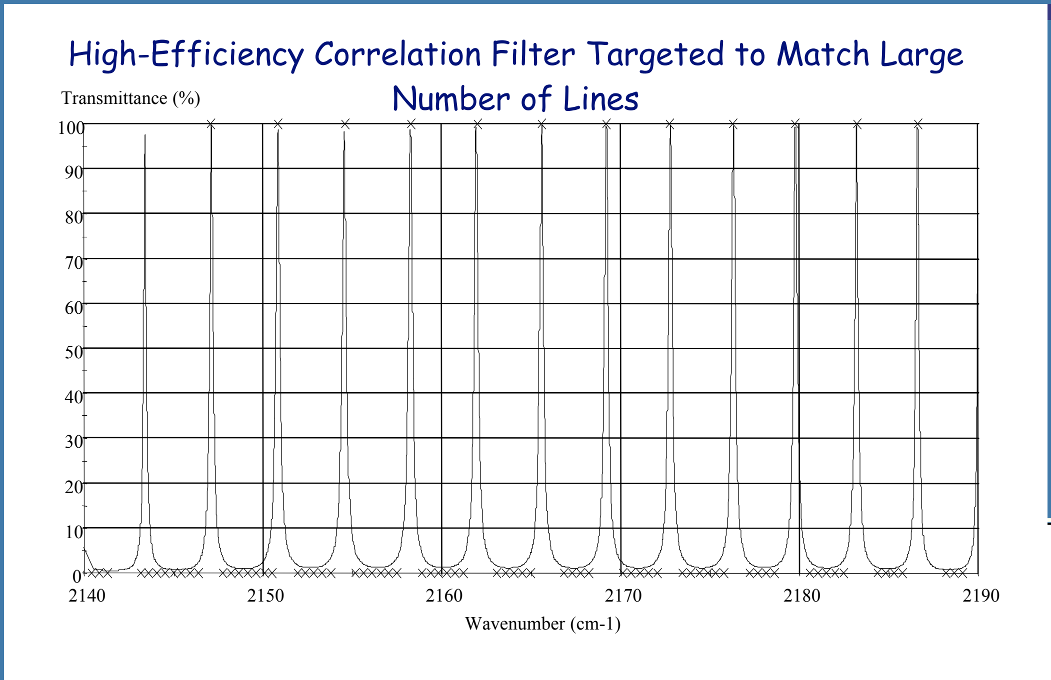
Conventional Fabry-Perot (Note Etalon transmission Function mismatched after a couple of lines)

Lines contaminated by other species avoided

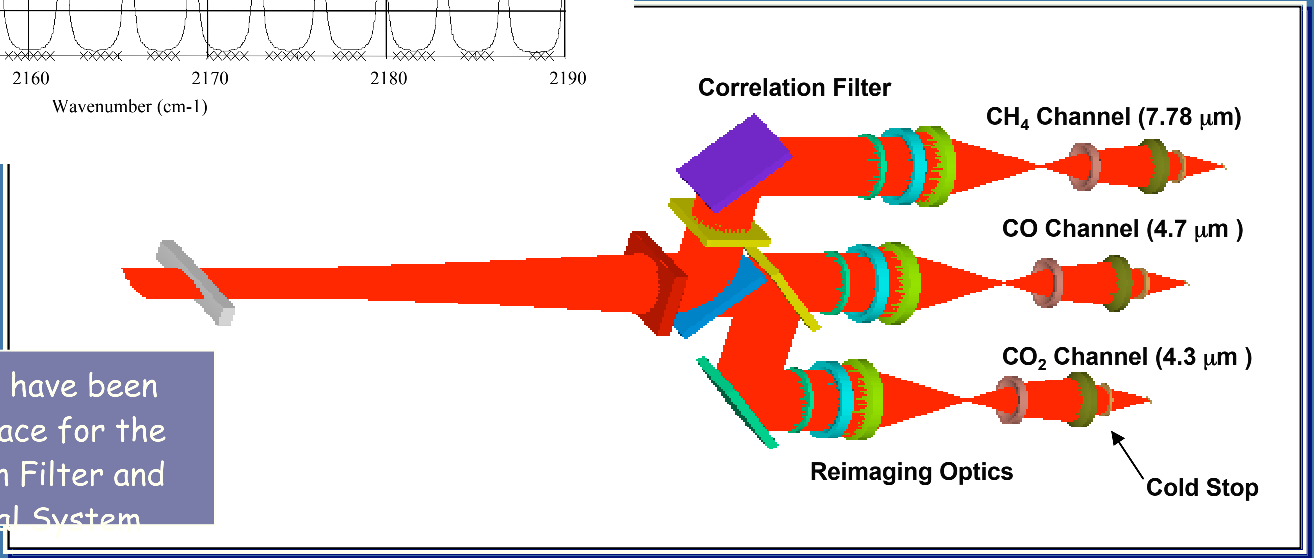
- **Correlation Filter Matches Several Spectral Lines to within ±0.02cm^{-1}**
- **Along-track imaging provides spectral sampling along lines**



Multi-Channel IMOFPS Concept



Three Co-Boresighted Channels provide simultaneous retrieval of CO, CO_2, and CH_4



Patent Applications have been filed by Ball Aerospace for the IMOFPS Correlation Filter and Anamorphic Optical System

Program Outline

Year 1 - Focus is on design and instrument development

- Optical design (telescope, collimator, spectrometer)
- Optically-Enhanced Dewar development
- Thermal design
- Mechanical design
- System-Engineering Tool Development
- Long-lead procurements (FPA, telescope)

Year 2 - Focus is on Assembly and Integration

- Optics procurement
- Mechanical fabrication
- Sub-System Assembly and Integration
- Test Facility Development
- System Configuration Studies

Year 3 –Test

- System-level testing of Laboratory Demo Instrument
- System Configuration Studies

Current Program Status

Focus is on Laboratory Demo Instrument Development

- **Optical design effort largely complete**
  - Tolerance analysis and piece-part drawings remain to be done
- **Optically-Enhanced Dewar**
  - Preliminary design and analysis complete
  - Final design to be completed this year
- **FPA Procurement**
  - Finalizing procurement
  - Electrical interface to be addressed
- **Mechanical Design**
  - Preliminary Design Complete
  - Final Design in Process
- **Thermal Engineering**
  - Initial thermal balance analysis complete
  - To be updated for final design

Summary

- SIRAS is a versatile approach to infrared imaging spectroscopy
- SIRAS-G program will provide hardware demonstration of this technology
- Aim to increase the technology readiness to TRL-6
- Exploring applicability of this technology to wide range of NASA Earth Science priorities
- A Long-term goal is to find an an airborne opportunity for SIRAS-G
  - *Goal is to obtain actual atmospheric temperature and water vapor (and possibly, trace gas) data from an airborne platform*
  - *This would go a long way in boosting confidence in this instrument concept in the scientific community*

And Finally, Thanks to the SIRAS-G Team!

- *Tom Kampe* – Principal Investigator, Optical Engineering
- *Dan Michaels* – SIRAS-G Systems Engineer
- *Brian Johnson* – Systems Engineering
- *Gregory Miecznik* – Systems Engineering / Radiative Transfer Analyst
- *Gary Mills* – Thermal Engineering
- *Paul Hendershott* – Mechanical Engineering
- *Holden Chase* – Optical Engineering (ASAP & FRED Modeling)
- *Peter Johnson* – Optical Engineering